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# Poster: High-Speed Data Dissemination over Device-to-Device Millimeter-Wave Networks for Highway Vehicular Communication

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**Abstract**—Gigabit-per-second connectivity among vehicles is expected to be a key enabling technology for sensor information sharing, in turn, resulting in safer Intelligent Transportation Systems (ITSs). Recently proposed millimeter-wave (mmWave) systems appear to be the only solution capable of meeting the data rate demand imposed by future ITS services. In this poster, we assess the performance of a mmWave device-to-device (D2D) vehicular network by investigating the impact of system and communication parameters on end-users.

## I. INTRODUCTION AND MOTIVATION

By 2020, ten million of vehicles with onboard communication systems and a range of autonomous capabilities will be rolled out to the market. Both the European Commission's Connected-Intelligent Transportation System (C-ITS) initiative and U.S. Department of Transportation acknowledged that connectivity is pivotal in making our roads safer by enabling vehicles to exchange real-time sensor data and driving intentions. Typically, a sensor setup includes multiple proximity sensors, camcorders, and light detection and ranging (LiDAR) systems. Exchanging real-time sensor data is a challenging task that requires wireless networks providing gigabit-per-second communications links [1].

Recently, millimeter-wave (mmWave) systems have been proposed as a means of overcoming the rate limitations of solutions based on LTE-A or the more traditional ITS-G5/DSRC [1]. Despite recent studies on device-to-device (D2D) mmWave networks [2], [3], none of these specifically refers or is directly applicable to D2D mmWave vehicular networks. With this regard, this poster focuses on the following research questions: **[Q1]** *What impact do communication or system parameters (such as the antenna beamwidth or traffic intensity) have on mmWave D2D vehicular networks?* and ultimately **[Q2]** *What is the maximum communication rate that can be theoretically achieved by a moving vehicle?*

## II. SYSTEM MODEL AND PROPOSED SOLUTION

We consider a system where cars and trucks drive along a highway section consisting of  $L$  parallel lanes. Assuming a system where vehicles drive on the left-hand side of the road and imposing  $L$  being an even number, vehicles driving on lanes  $1, \dots, L/2$  move toward the East-to-West direction. On the other hand, lanes  $L/2 + 1, \dots, L$  are associated with the West-to-East driving direction. The  $\ell$ -th traffic lane is characterized by an overall traffic intensity equal to  $\lambda_\ell$ . We regard with  $\epsilon_\ell$  the probability of a vehicle in lane  $\ell$  being a

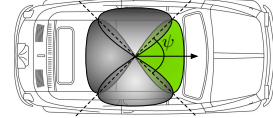


Fig. 1. Sectorized approximation of the array pattern with  $\psi = 90^\circ$ . The picture shows the antenna boresight pointing toward the front of the vehicle.

truck. Thus, the density of cars and trucks in lane  $\ell$  is equal to  $(1 - \epsilon_\ell)\lambda_\ell$  and  $\epsilon_\ell\lambda_\ell$ , respectively.

Since there are no restrictions preventing trucks from driving in specific traffic lanes, they can obstruct a direct link between two or more cars. In particular, whenever a truck blocks the direct link between two cars, the truck is treated as an impenetrable blockage, and no non-line of sight (NLOS) communications between the cars can occur. If there is line of sight (LOS) between two cars, transmissions will be attenuated by a path loss equal to  $\ell(r) = \min\{1, Cr^{-\alpha}\}$ , where  $C$  is the path loss intercept factor,  $\alpha$  is the path loss exponent and  $r$  is the distance between a transmitter and a receiver [1].

Cars are equipped with antenna arrays capable of performing directional beamforming onto the azimuth plane (see Fig. 1). To capture this feature, we follow the sectorized approximation of an array pattern proposed in [3]. In addition, let  $\psi$  be the beamwidth of the antenna main lobe, the azimuth plane is divided into  $R = 2\pi/\psi$  regions, assuming  $\psi$  expressed in rad). We impose that each antenna boresight can only be horizontally steered uniformly at random with steps of  $\psi$  rad. As such, an antenna boresight can only point toward one the  $R$  possible directions with a probability of  $1/R$ .

Each car can either be in receiving or transmitting mode with probability  $p_{RX}$  or  $p_{TX} = 1 - p_{RX}$ , respectively. Communications among trucks have not been considered. The access to the media is regulated by a media access control (MAC) layer, which implements a time slotted system. Each slot has a duration equal to  $\tau$  and it is divided into  $S$  subslots, each with a duration equal to  $\tau/S$ . Consider a car  $o$  in receiving mode. At the beginning of each slot, car  $o$  (i) randomly steers its antenna beam toward one of the  $R$  directions, (ii) detects all the transmitting cars  $\mathcal{C}_o$  (here after referred to as *transmitting cluster*) that can be received with a power not smaller than  $\bar{T}$ , (iii) informs each member of the transmitting cluster to transmit on a specific subslot, and (iv) puts itself in listening mode. For simplicity, we assume that  $S$  is larger than the

TABLE I  
MAIN SIMULATION PARAMETERS.

Parameter	Value
Road length, $L$ , Lane width	20 km, 4, 3.7 m
$\lambda_\ell$	$\{10, \dots, 60\} \cdot 10^{-3}$
$\epsilon_1, \dots, \epsilon_4$	$[0.1, 0.05, 0.05, 0.1]$
Mobility model	Krauss car-following mobility model [1]; maximum vehicle speed equal to 96 km h <sup>-1</sup> (trucks), 112 km h <sup>-1</sup> (cars).
Vehicle dimensions	11.2 m $\times$ 2.52 m (trucks); 4 m $\times$ 2.52 m (cars);
Carrier frequency, $W$	28 GHz, 2.16 GHz
$C, \alpha$	Free space path loss at 1 m, 2.6 [1]
$P_{RX}, P_{TX}$	0.5
$T, m, P_t$	Set to allow a 100 m coverage, 3, 1 W [1]

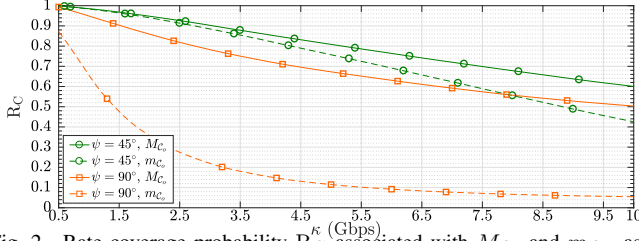


Fig. 2. Rate coverage probability  $R_C$  associated with  $M_{C_o}$  and  $m_{C_o}$ , as a function of  $\kappa$ , for  $(1 - \epsilon_2)\lambda_2 = 5.7 \cdot 10^{-2}$  and  $\psi = \{45^\circ, 90^\circ\}$ .

cardinality of  $C_o$ . The signal-to-noise-plus-interference ratio (SINR) at car  $o$  associated with transmissions received from the  $i$ -th car in  $C_o$  is defined as follows:

$$\text{SINR}_o = \frac{|h_i|^2 \Delta_i \ell(r_i)}{\sigma + I}, \quad \text{where } I = \sum_{j \notin C_o} |h_j|^2 \Delta_j \ell(r_j). \quad (1)$$

We model the channel between any transmitting and receiving car as a Nakagami model with parameter  $m$ . Hence,  $|h_i|^2$  follows a gamma distribution (with shape parameter  $m$  and rate equal to 1). Term  $\Delta_i$  represents the overall transmitting and receiving antenna gains and  $\sigma$  is the thermal noise power normalized with respect to the transmission power  $P_t$ . All the transmissions from those cars, which do not belong to  $C_o$  are regarded as interference, which has power  $I$ .

### III. NUMERICAL RESULTS AND DISCUSSION

Through Monte Carlo simulations having their main parameters set as reported in Table I, we estimate: (i) the SINR outage probability  $P_T(\theta) = \mathbb{P}(\text{SINR}_o < \theta)$  of car  $o$  for a threshold  $\theta$ , and (ii) the rate coverage probability  $R_C(\kappa)$  of car  $o$  for a threshold  $\kappa$ , defined as the probability that car  $o$  experiences a reception rate not smaller than  $\kappa$ . In this performance investigation, we focus on cars (in receiving mode) driving on lane 2 as their communications will be affected by a stronger interference component compared to the users circulating on an outermost lane.

Fig. 2 shows  $R_C$  as a function of  $\kappa$  for a traffic density equal to 60 cars per-kilometer ( $\lambda_\ell = 6 \cdot 10^{-2}$ , for  $\ell = 1, \dots, L$ ), for  $\psi$  equal to  $45^\circ$  and  $90^\circ$ . The figure also compares the rate coverage probability of transmissions originating from user  $M_{C_o}$  and  $m_{C_o} \in C_o$  determining the maximum and minimum value of  $\text{SINR}_o$ , respectively. From Fig. 2, it follows that the more the beamwidth reduces, the more the rate that user

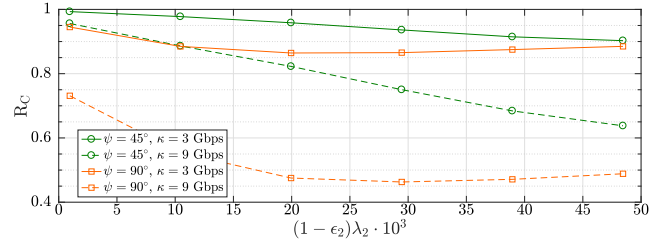


Fig. 3. Rate coverage probability  $R_C$  associated with  $M_{C_o}$  as a function of  $(1 - \epsilon_2)\lambda_2$ , for  $\psi = \{45^\circ, 90^\circ\}$ .

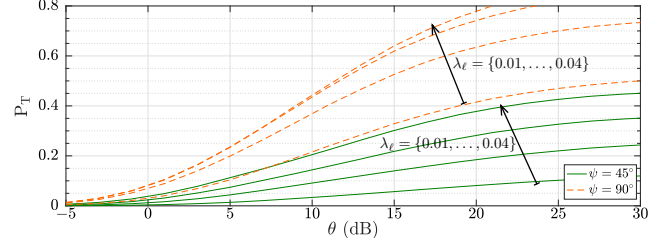


Fig. 4. SINR outage probability  $P_T$  associated with  $M_{C_o}$  as a function of  $\theta$ , for  $\lambda_2 = \{0.01, \dots, 0.04\}$  and  $\psi = \{45^\circ, 90^\circ\}$ .

$o$  can expect to achieve from the transmitting cluster will increase. Furthermore, the figure suggests that decreasing  $\psi$ , significantly reduces the performance gap between  $M_{C_o}$  and  $m_{C_o}$  – thus reducing the performance heterogeneity in  $C_o$ .

Fig. 3 shows the rate coverage probability associated with user  $M_{C_o}$  as a function of the car density on lane 2, for  $\kappa$  equal to 3 Gbps and 9 Gbps. We observe that  $R_C$  increases as the beamwidth, the value of  $\kappa$  or the vehicle density decrease. These conclusions are further reinforced by Fig. 4 showing that the SINR coverage probability for different values of  $\lambda_2$ .

### IV. CONCLUSIONS

The adoption of a slotted communication system determines that cars belonging to the same transmitting cluster do not interfere among themselves while communicating to user  $o$ . Despite this, the overall interference contribution is not negligible. In particular, with regards to **[Q1]**, for a fixed antenna beamwidth, the rate coverage probability and hence, the SINR outage probability are substantially impacted by the density of vehicles. In addition, the smaller the value of  $\psi$  the higher the rate coverage probability or equivalently, the smaller the SINR outage probability. That holds true essentially because smaller values of  $\psi$  are associated with higher antenna gains. Finally we answer to **[Q2]** by noting that, for  $\psi = 45^\circ$ , user  $o$  can successfully support incoming data streams from  $M_{C_o}$  or  $m_{C_o}$  at a rate greater than 4.6 Gbps or 4.3 Gbps with a probability of 0.8.

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